What is a plasma?
Why should anyone care?

T. Intrator

- P-24 - Plasma Physics
  - –Magnetic Fusion energy
    - •Magnetized target Fusion
    - •Field Reversed configurations
  - –Plasma astrophysics
    - •Magnetic reconnection
    - •Magnetoresistive instability
    - •Relaxation, self organization
    - •Laser (ICF) plasma

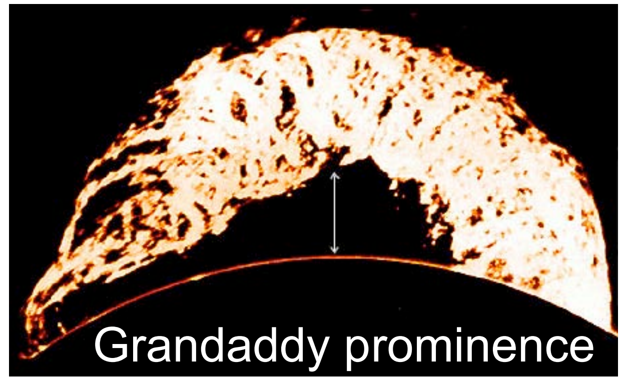
abstract

This introduction will define the fourth state of matter, ie what a plasma is, where we find plasmas on earth and beyond, and why they are interesting to study. Some of the applications to many consumer items, fusion energy, scientific devices, satellite communications, etc. will be discussed. Since 99% of our universe is comprised of plasma, plasma physics also forms the basis of many important phenomena in astrophysics, space physics, and magnetosphere physics in our solar system. We will discuss how to make plasmas, what they are used for, some theoretical framework including the connection between kinetic and fluid descriptions, quasi neutrality, Debye shielding, ambipolar electric fields, some plasma waves. We will include some hands on demonstrations.

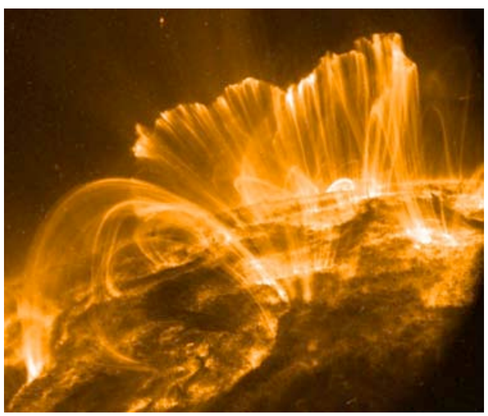
OUTLINE

- What is a plasma, different examples?
- Where to look? How to create?
- theoretical framework
  - Particles & fluids
  - Maxwell's equations
  - Confinement
  - Shielding, sheath, Debye length
  - Waves
  - Magneto hydro dynamics
- some applications
- summary

Large Scale Plasma Structure in the Universe



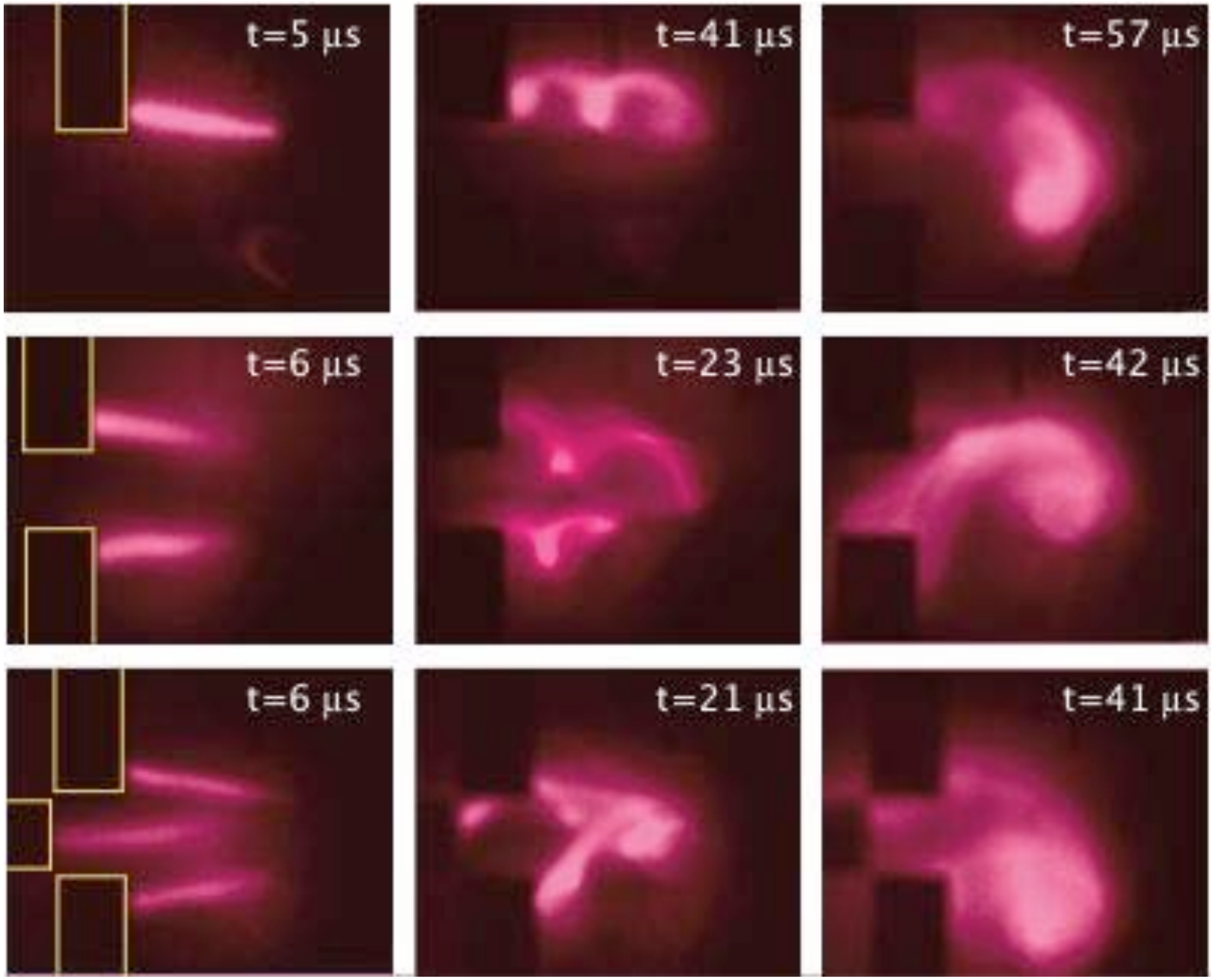
June 4, 1946 High Altitude Observatory…
http://solar-center.stanford.edu/compare



TRACE satellite VUV images

Coronal arches, magnetic structures

Current ropes modeled in the laboratory

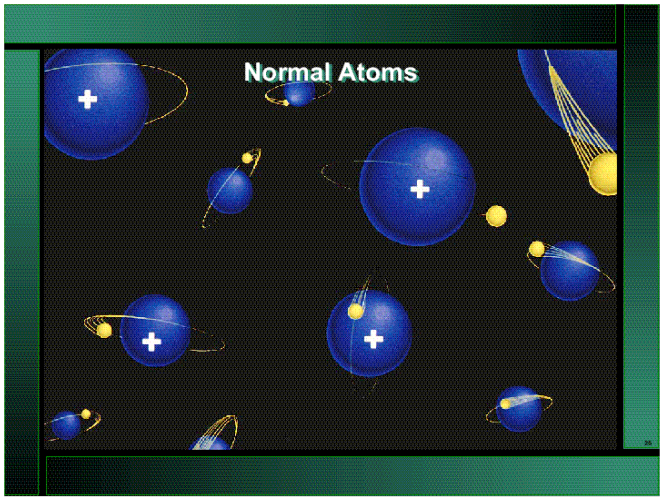


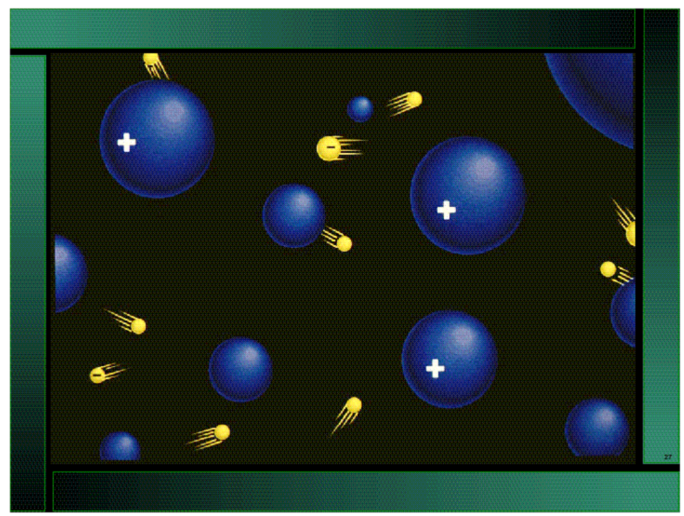
Northern lights - aurora borealis
electron acceleration from 1 RE down polar field lines

What is a plasma?

- Plasma state is the "fourth" state of matter
- As a solid is heated
  - Bonds between adjacent molecules loosen => solid (1/40 eV)
  - More heat => loosens up the lattice => Liquid state
  - More heat => neighboring bonds are broken => gas
  - More heat => molecular collisions => dissociate to atoms
  - More heat => collisions knock off electrons => plasma (>2eV)
    - neutral particles, ions & electrons
    - $k_B T \approx$ few eV, equivalent to chemical bonds
    - 99% of the universe
- solid-liquid-gas-plasma

Normal atoms are charge neutral



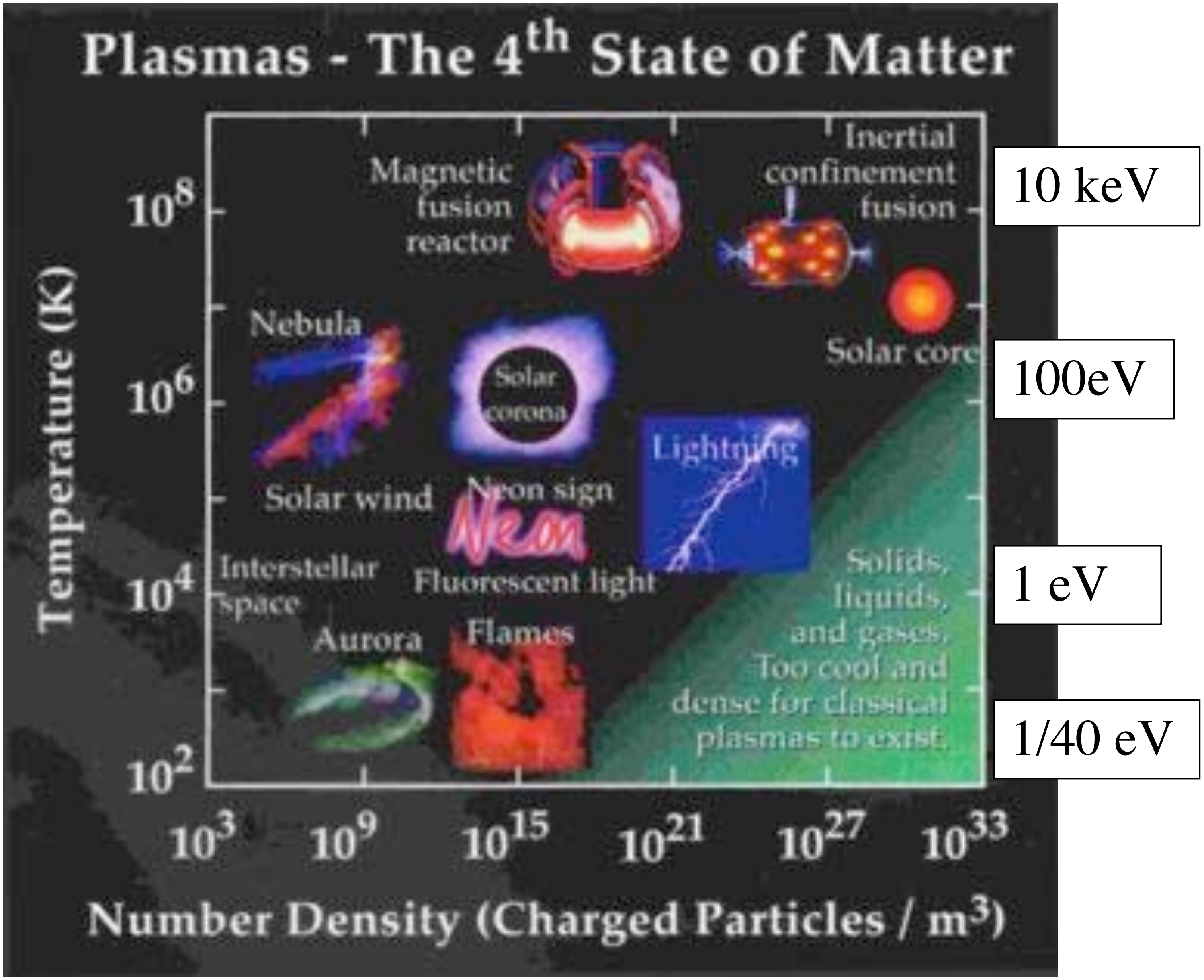


Add some thermal energy

electrons acquire enough energy to escape from atomic binding forces => ions & electrons

Do plasmas differ from everyday materials?

- With most materials, nearest neighbor interactions determine properties
- BUT: In a plasma,
  - charge separation generates electric fields
  - Charge flow generates currents and magnetic fields
  - These fields create "action at a distance" - Collective effects
  - A huge range of phenomena
    - Startling complexity
    - Many practical applications
    - Relevant to 99% of the universe that is plasma
    - Occasionally a confluence of physics with striking beauty


Plasmas - The 4th State of Matter
Magnetic fusion reactor
Inertial confinement fusion
Nebula
Solar core
Solar corona
Lightning
Solar wind
Neon sign
Interstellar space
Fluorescent light
Solids, liquids, and gases, Too cool and dense for classical plasmas to exist.
Aurora
Flames
Temperature (K)
10^8
10^6
10^4
10^2
10^3
10^9
10^15
10^21
10^27
10^33
Number Density (Charged Particles / m^3)
10 keV
100eV
1 eV
1/40 eV

Plasma - πλασμα

- The term plasma was originally coined by Langmuir and Tonks in 1929
  - πλασμα
  - In Greek, this means *moldable substance* or jelly

- Today the term “plasma”is used quite generally to describe quasi neutral systems of charged particles
  - Plasma physics is the study of the its behavior
- Analogous to quantum mechanics - both wave and particle properties
  - Plasmas behave both as collections of particles as well as a fluid
  - Fluid and electromagnetic waves, flows

sketch of the history

- 1920's Langmuir - vacuum tubes
- 1930's Appleton - ionosphere
- 1950's nuclear fusion
- 1960's solar wind, stellar interiors
- 1980's industrial applications
    - Semiconductor industry
    - Plasma processing of materials
    - Plasma torch

Where do we find plasmas?

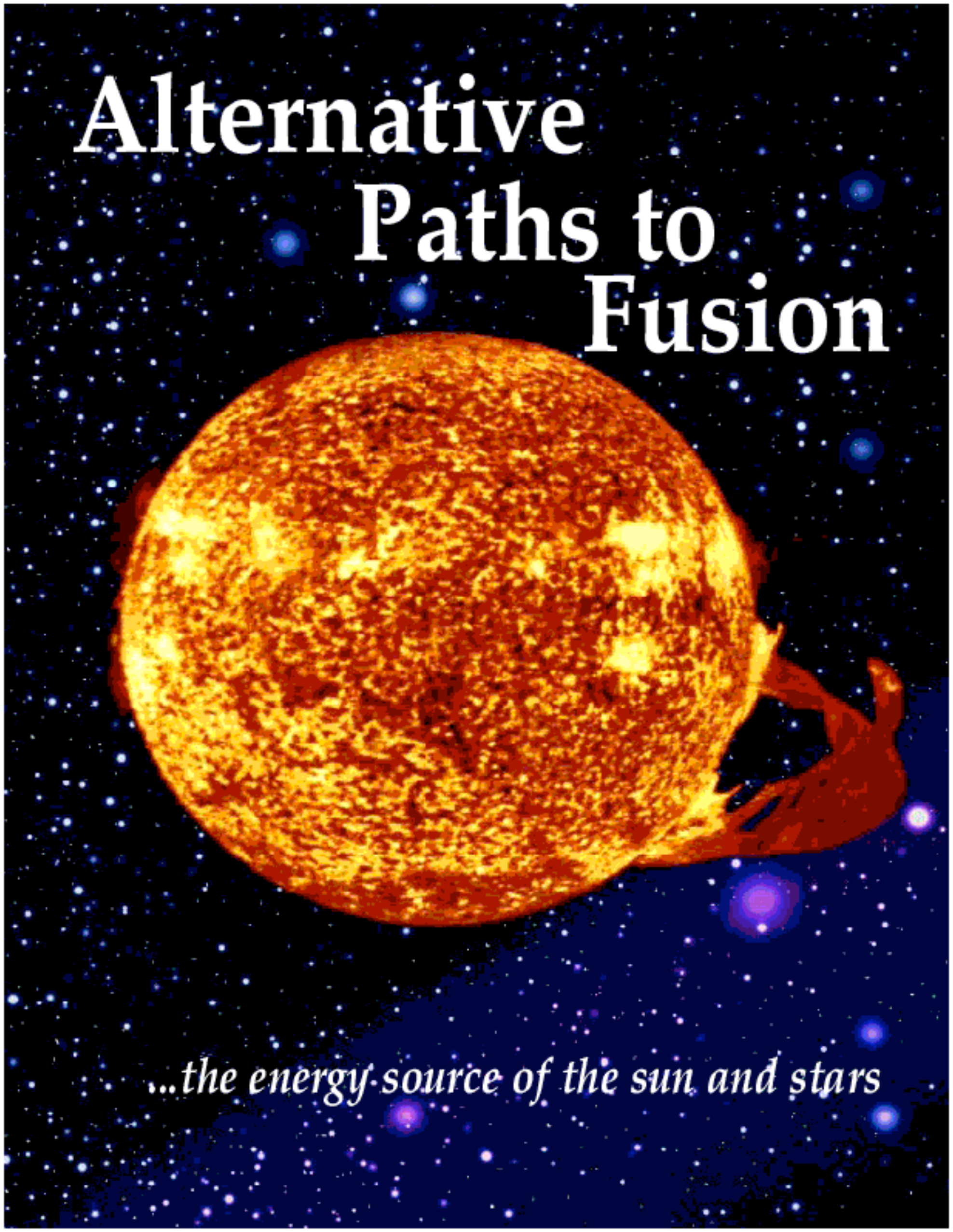
- On earth in nature
  - Lightning
  - Aurora
- in everyday life
  - Spark plug, arc welder, gas stove, fluorescent light bulb,
- Beyond our earth's atmosphere
  - Magnetosphere pervades our solar system
  - Plasma system formed by the interactionof the earth's magnetic field and the solar wind
- Stars are made of plasma, including our sun
- Most of the universe is made up of plasma

How to make a plasma?

- Heating a container with gas inside is not practical
  - the container would need to be as hot as the plasma, ie ionized as well
- Typically in the laboratory a small amount of gas is heated and ionized. Power absorbtion can occur when you
  - Pass a current through it
  - Shine radio, light waves through it
  - Shock it
- Container must be cooled, or insulated (e.g. with a magnetic field

What are plasmas used for?

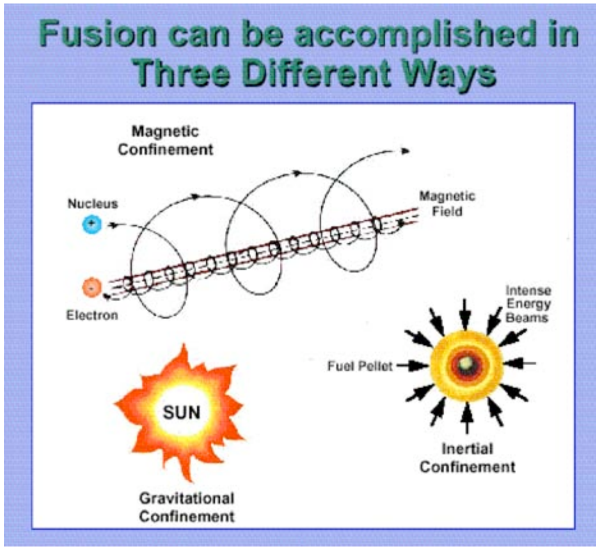
- Gas lasers, visible, X-ray wavelengths
- Plasma processing of materials
  - Plasma assisted chemistry
  - etching & deposition on semi conductors, sunglasses …
- Lighting
- Next generation of particle accelerators
- Production of power from thermonuclear fusion
  - $D^+ + T^+ \Rightarrow \alpha(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV})$, $T_i > 10\mathrm{keV}$
  - Magnetic field helps decrease losses (increase confinement)
  - Non carbon fuel cycle
  - "greener" than fission breeder reactors

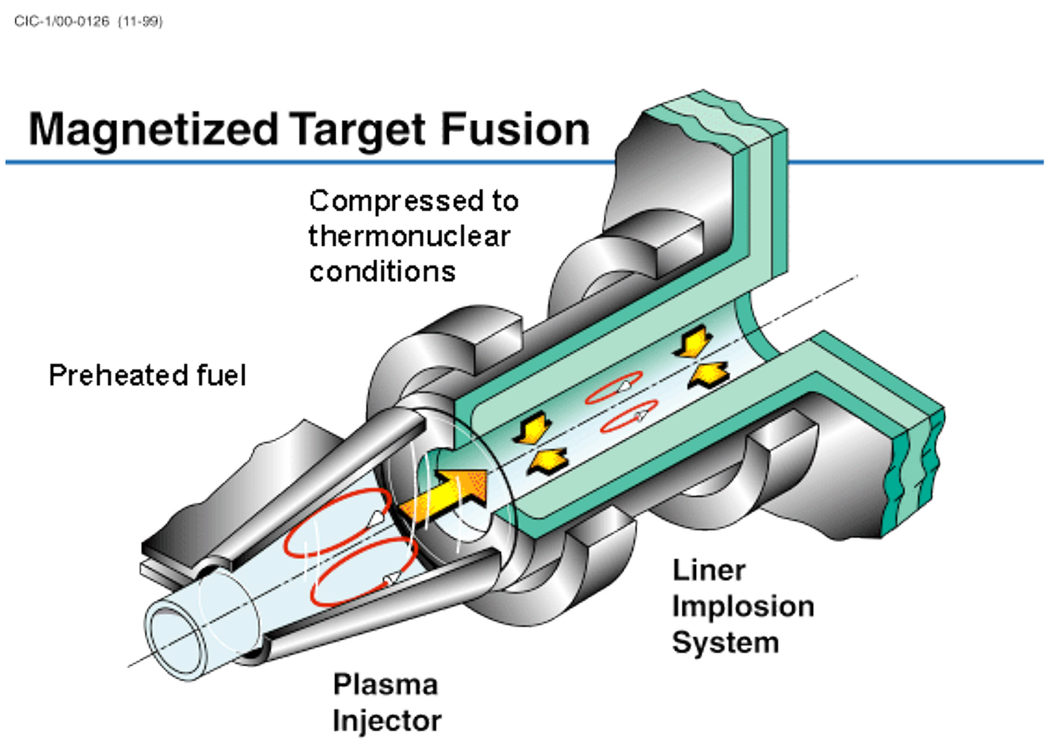

Alternative
Paths to
Fusion
...the energy source of the sun and stars

Why fusion plasma science?

- Dual nature of fusion research.
  - *Grand Challenge* frontiers of science and technology
  - Understand behavior of plasmas of most of the baryonic universe
  - creation of a non-fossil energy source … could power large cities and industries
- LANL missions
  - Energy security
  - Threat reduction: neutron sources for active interrogation, interpret satellite data
  - Pushes limits of multi scale computing
  - NWP: high energy density plasmas
- many other applications

Applications of plasma science to the energy crisis





Theoretical framework is diverse

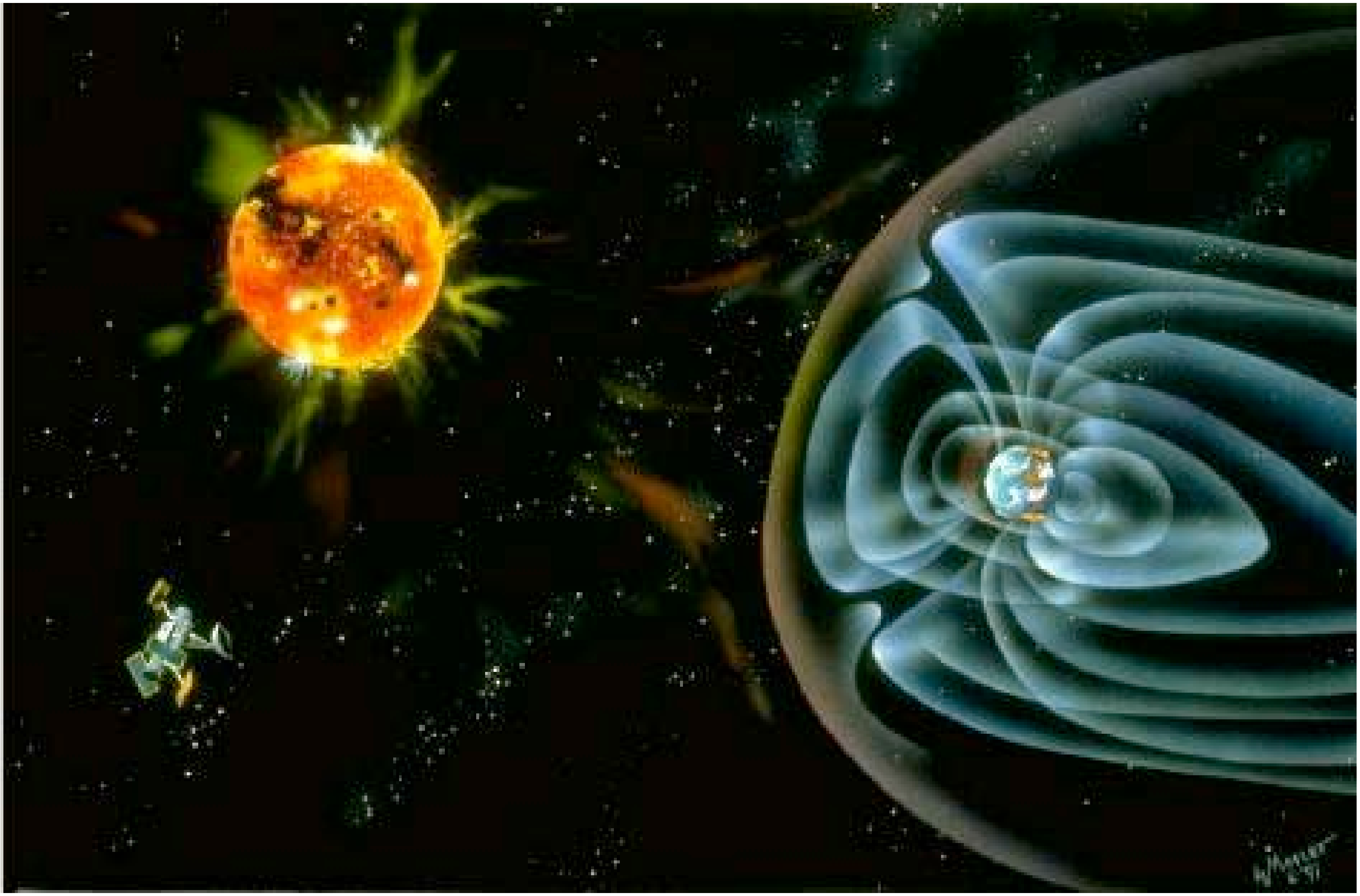
- Start with gas with charged particles
  - *Kinetic theory* of gases can be extended, include magnetic fields
  - Plasma kinetic theory offers unique insights into transfer of energy between waves and particles
- Similarity to galactic dynamics
  - Many body problem for inverse square fields
    - *Coulomb* for charged particles q/r^2
    - *Gravity* for stars mMG/r^2
- Fluid dynamics with high conductivity
  - *Magneto Hydro Dynamics* - (MHD)
  - *Flows* convect magnetic fields, relaxation, self organization
- Similarity to a solid
  - Collective wave modes are described by a *dielectric tensor*
  - Key properties- *polarization, dispersion* resemble solid state physics
- Self consistency is a challenge

This fluid "feels" electromagnetic forces

- Since the plasma state is a fluid that includes
  - High electrical conductivity
  - free positive and negative charges => electric fields
  - Charge movements = currents
  - Currents & magnetic fields must close on themselves
- Plasmas are influenced by electric and magnetic fields
  - This leads to a diverse "zoo" of properties
  - Self consistent structure is fascinating
  - Vorticity, particles <=> waves, turbulence, chaos …
  - Self organization

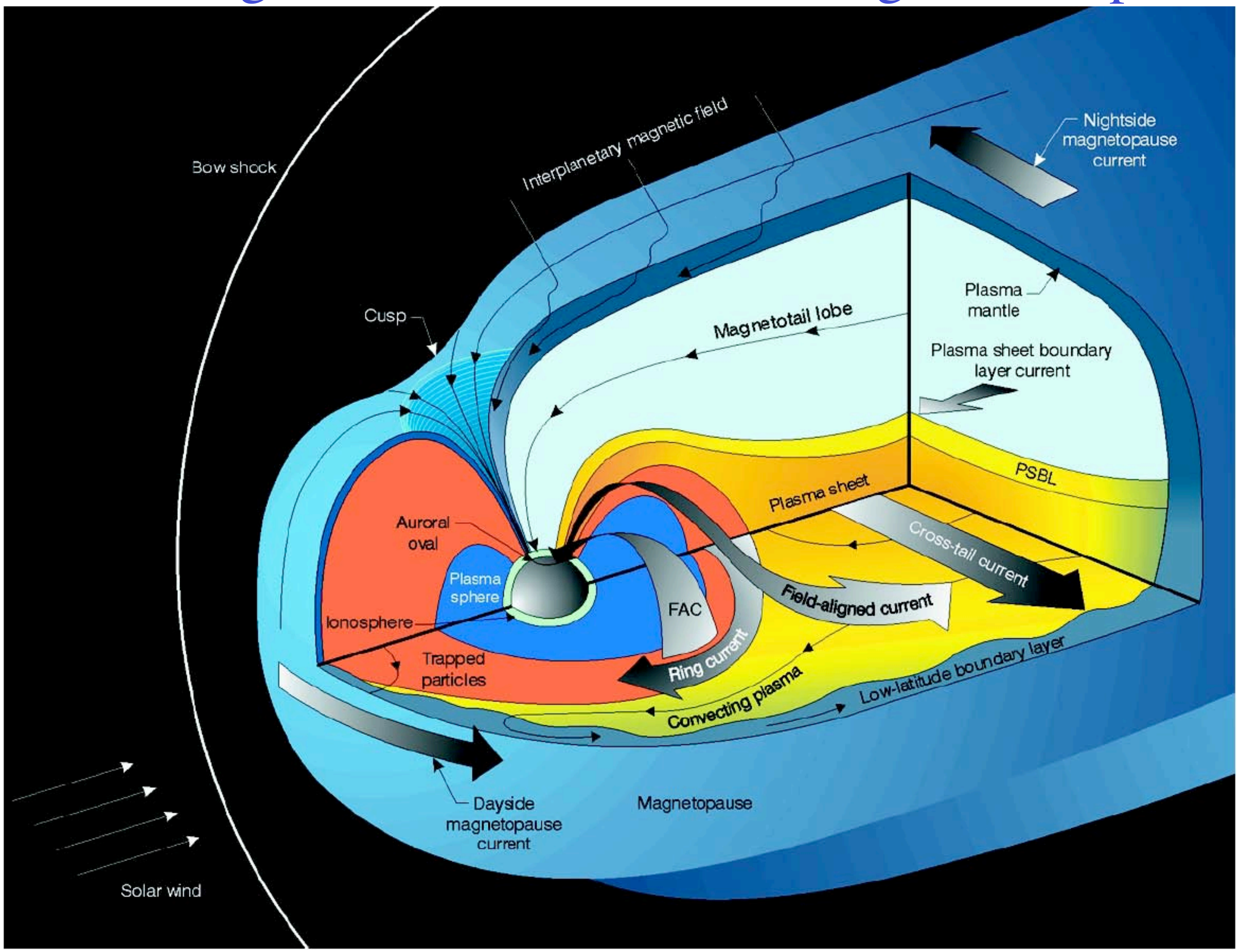
3D view of solar wind, bow shock

probably typical of planetary magnetospheres



Earth+solar wind+dipole magnetic field

=> convecting field lines, bowshock, magnetotail, plasmoid



Maxwell's equations (SI units)

describe electromagnetic fields

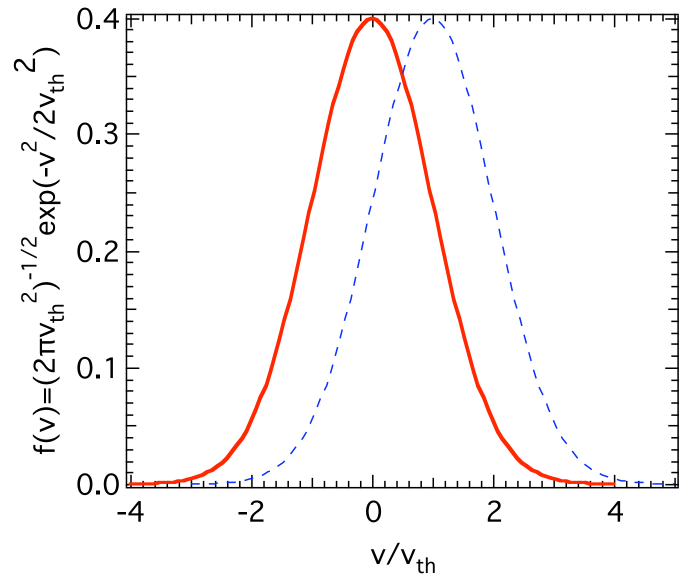
Faraday's Law	$\nabla \times E = -\dfrac{\partial B}{\partial t}$
Loop currents and magnetic field	$\nabla \bullet B = 0$
Poisson's eqn, charge density	$\nabla \bullet \varepsilon_0 E = e(n_i - n_e) = \rho$
Ampere's law	$\nabla \times B = \mu_0 J + \dfrac{1}{c^2}\dfrac{\partial E}{\partial t}$

Current conservation $\partial(en)/\partial t + \nabla \bullet J = 0$

Lorentz force equation $F = q(E + v \times B)$

Connection between particle and fluid picture

- Velocity distribution function
  - $f_v(\mathbf{x},t)$
  - Probability of a particle with a chosen velocity
  - Thermal jitter => Maxwellian distribution
  - $f(v) =$
    - $(2\pi v_{th}^2)^{-1/2} \exp(-(v-v_D)^2/2v_{th}^2)$
    - $T = m v_{th}^2$



Averaged fluid quantities

- Density $n/n_0 = \int f(v)\, dv$
- Thermal velocity $V_{th}^2 = \langle v^2 \rangle = \int v^2 f(v)\, dv$
- Drift velocity $v_D = \langle v \rangle = \int v\, f(v)\, dv$

Charge neutrality & Debye length

- Consider a plasma, that initially has
  - Thermo dynamic equilibrium: Maxwell-Boltzmann distribution
  - uniform charge density $n_{i0} \approx n_{e0}$
  - zero electric field
- How does the charge density behave when we attempt to change it?
- Suppose electron density drops from $n_{e0} \Rightarrow (1-\delta)n_{e0}$, $n_i(x) \approx$ constant
- If there were no change in electron density the equation for potential would be
  - $E = -\nabla\phi$
  - $\nabla \bullet \varepsilon E = e(n_i - n_e)$ divergence of E = charge density
  - $-\varepsilon\nabla^2\phi = e\,\delta n$

Charge neutrality & Debye length

kinetic energy

- Maxwellian electron distribution f(energy) in 1 dimension
  - $-\varepsilon\, d^2\phi/dx^2 = e\,\{n_{i0} - n_{e0}\exp[-(e\phi/T + v^2/2v_{th}^2\,)]\}$ & integrate over velocity
  - $n(x)/n_{e0} = \exp[-(e\phi(x)/T_e)]$

    Potential energy
  - expand the ODE in terms of small ϕ/T,
    - $-\varepsilon\, d^2\phi/dx^2 \qquad \approx e[n_{i0} - n_{e0}\,(1- \phi/T)]$
    - $d^2\phi(x)/dx^2 \qquad \approx -\, e\, \delta n_{e0}\,(e\phi(x)/T) / \varepsilon$
- Which has exponentially decaying solutions
  - $\phi(x) \approx \exp[-x/\lambda_D]$
  - $e\phi(x)/T \approx \exp[-x/\lambda_D]$ normalize this equation to be dimensionless
  - $\lambda_D = [\varepsilon_0 T/\,(e^2 n_e)]^{1/2}$ *Debye length* $\lambda_D(\mathrm{cm}) = 740\ [T_e(\mathrm{eV})/n(\mathrm{cm}^{-3})]^{1/2}$
- *Debye length* λ_D is the characteristic exponential decay *length*
  - Potential and electric fields from a point charge are shielded out by the sea of other charged particles on λ_D scales
  - definition of a plasma is that many particles exist in a *Debye sphere*
    - $n\,\lambda_D^3 \;>>1$
    - Validate statistical assumption of small departures from equilibrium

Quasi neutrality, ambipolar electric fields, sheath, boundary layer problem

– $e\phi(x)/T \approx \exp[-x/\lambda_D]$

– Φ/T concave down for ion surplus

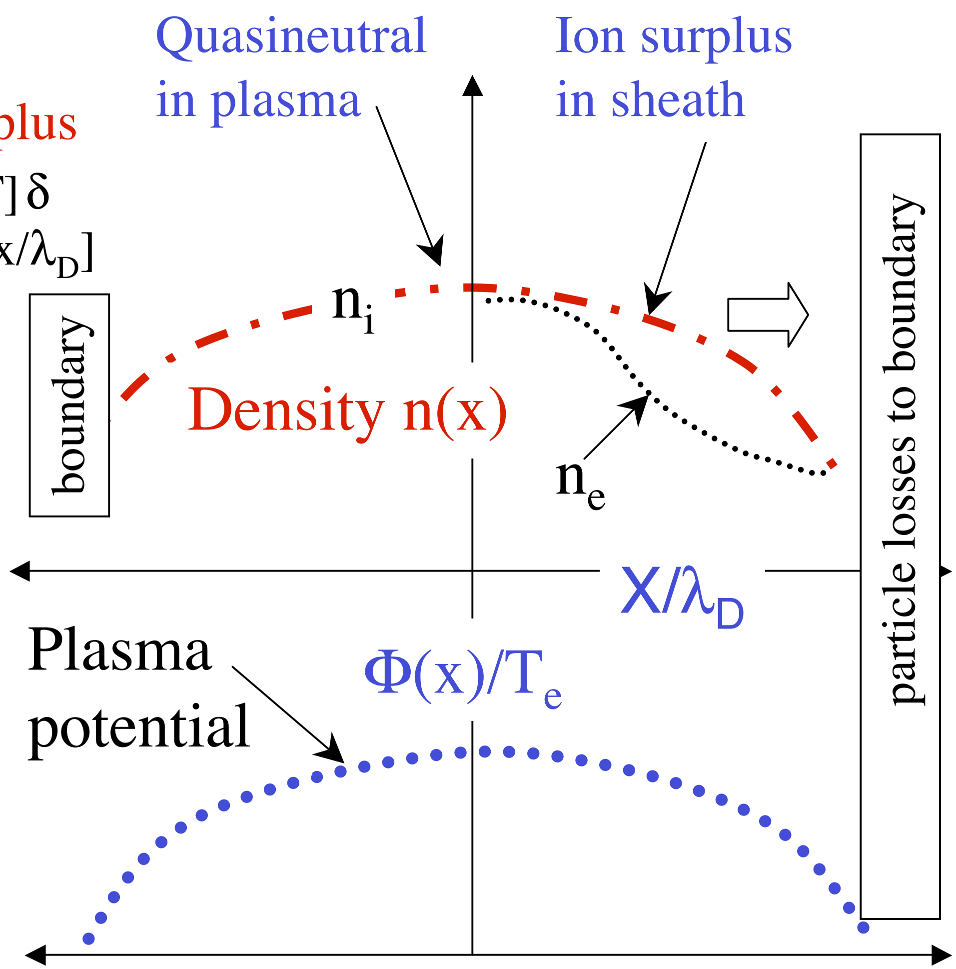
– $d^2[e\phi(x)/T]/dx^2 \approx -(x^2/\lambda_D{}^2)[e\phi/T]\,\delta$

$n/n \approx (x^2/\lambda_D{}^2)\exp[-x/\lambda_D]$

– $\approx \exp[-e\phi/T]$

- scales with density difference between mobile electrons n_e and heavy ions n_i

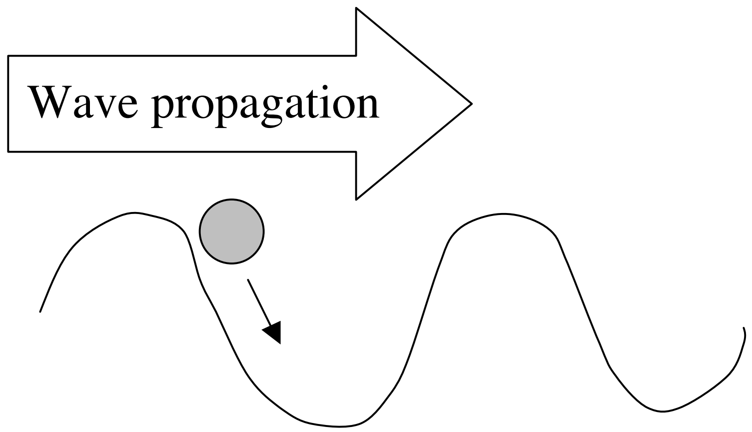
- electrons escape faster than ions but are held back by self consistent electric field
- Scale length is λ_D



Plasma waves *vs* free space waves

- charged particles are tightly coupled to electric and magnetic fields in the plasma
- Wave properties depend on the the dielectric and magnetized medium
  - Charged particles can move freely along a B field
  - Movement across the B field is inhibited
  - Anisotropic wave propagation and properties

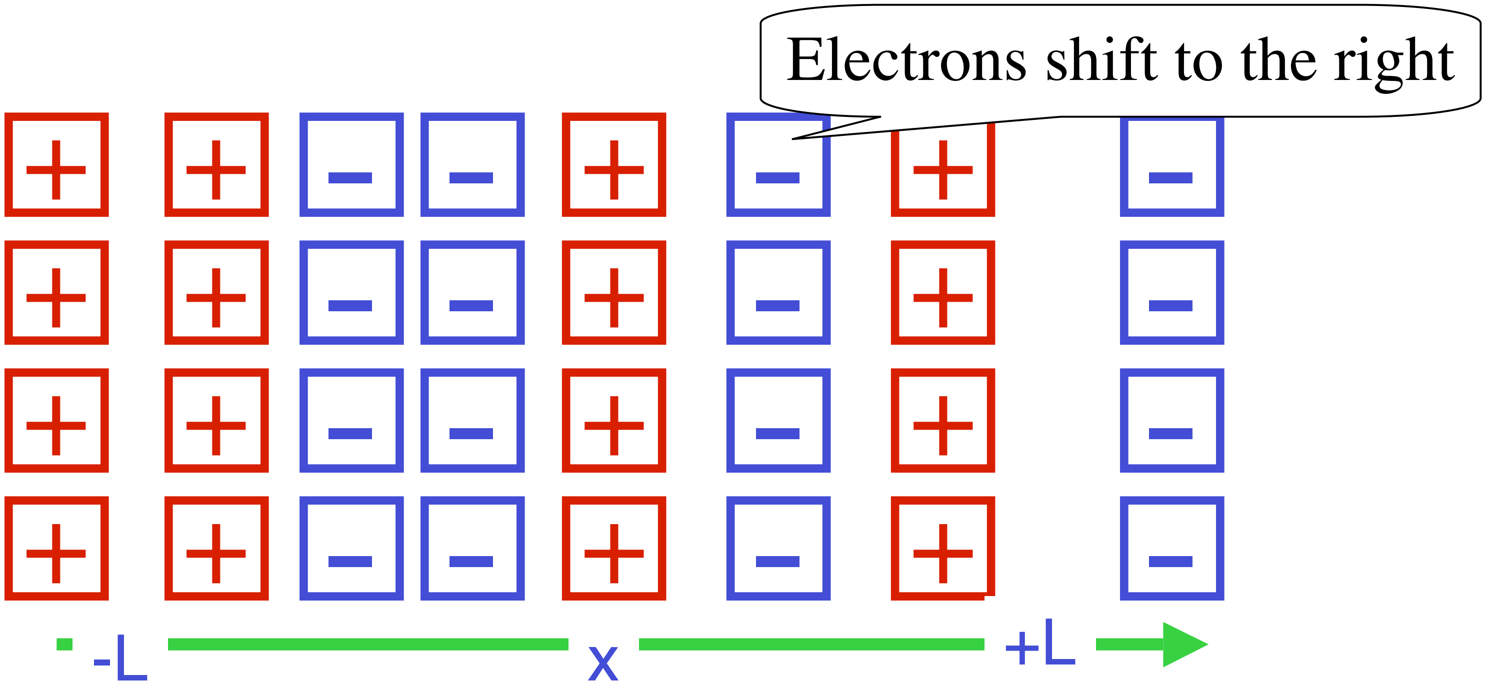
Landau Damping



- Particles "surf" on wave if $v_\phi > v_{particle}$
- Wave gains energy from particle if $v_\phi < v_{particle}$

Electron plasma oscillations

- Consider one dimensional motion
- Sheet of electrons centered at x
- Now move e- distribution to right, x'=x + ξ
  - Excess positive charge neξ per unit area
  - Field points to right $\mathbf{E} = ne\varepsilon_0\xi$



- E field points to right, because of charge separation

Electron plasma oscillations

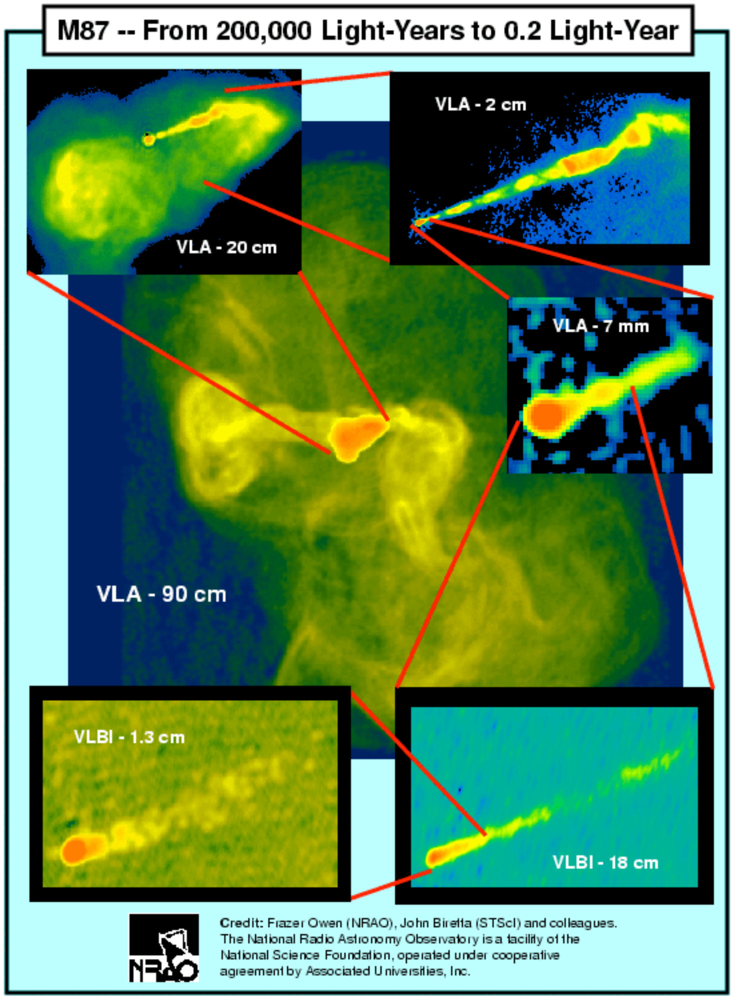
- Equation of motion is $f = ma = m\, d^2x/dt^2$
- $-eE = m\, d^2\xi/dt^2$
  - Recall $E = ne\varepsilon_0\xi$ so that
  - $m\, d^2\xi/dt^2 = -e\,(ne\varepsilon_0\xi)$
  - $d^2\xi/dt^2 + e^2\, n\, \varepsilon_0\xi/m = 0$

- The ODE for displacement ξ is then
  - $(d^2/dt^2 + \omega_{pe}^2)\,\xi = 0$
  - Where $\xi(t) = \xi_0\,[\exp(+\, i\omega_{pe}t\,) + \exp(-\, i\omega_{pe}t\,)]$
  - $\omega_{pe}^2 = n\, e^2\varepsilon_0\,/m$ is the electron plasma frequency

Magneto Hydro Dynamic approximation

- If a magnetized plasma has disturbances that are sufficiently slow and on a large spatial scale
  - Mobile electrons can prevent the buildup of any electric field that moves with the plasma
    - Fields are “stuck” in plasma reference frame - *frozen flux* theorem
  - Higher frequency modes of oscillation and wave propagation do not play a role
  - Behavior simplifies substantially
- Magneto Hydro Dynamic (MHD) approximation

Galactic jets - fluid flow and radiation powered by annihilation of magnetic fields (reconnection)?



J and B relax till JxB forces minimize, J•B maximize

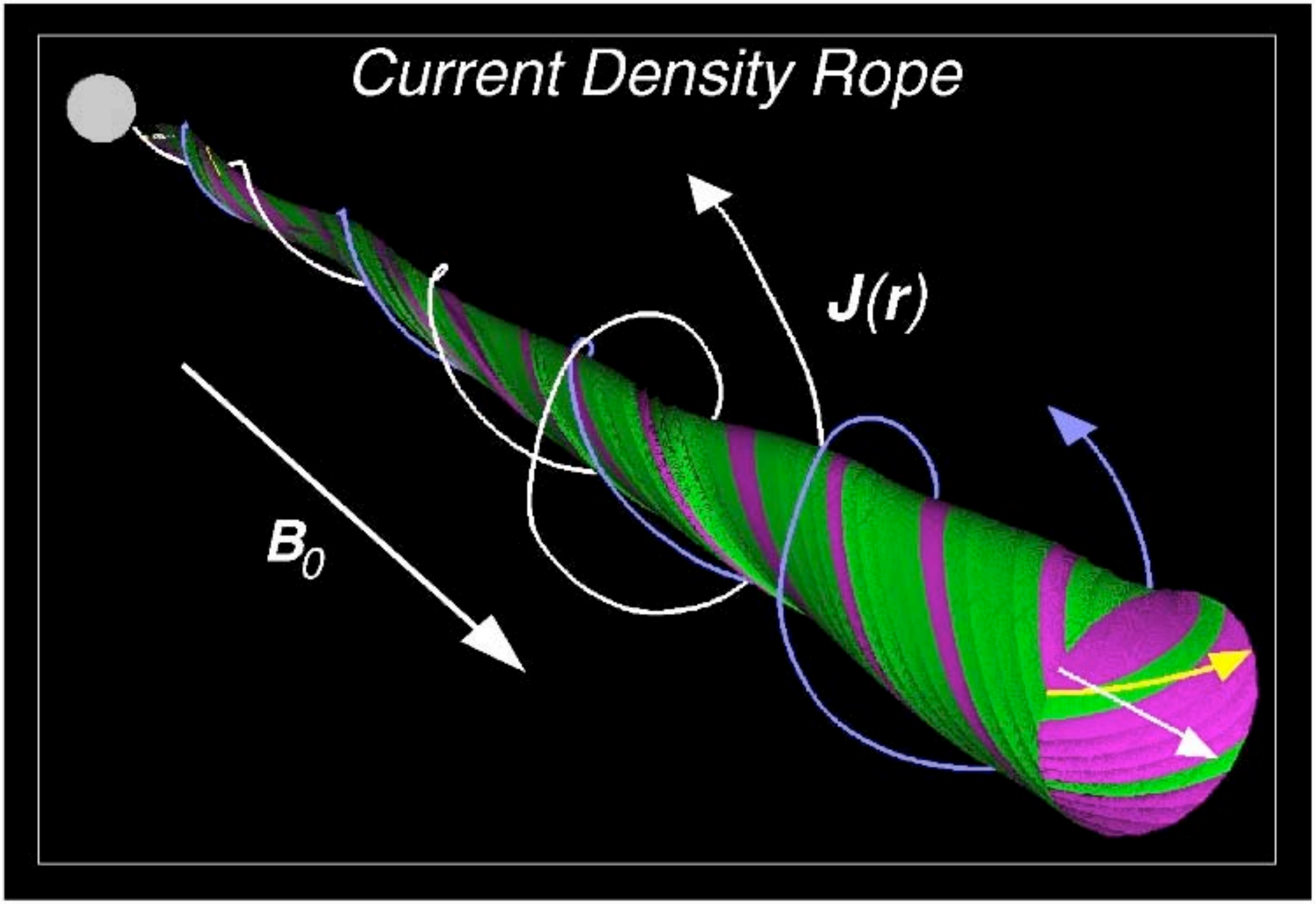
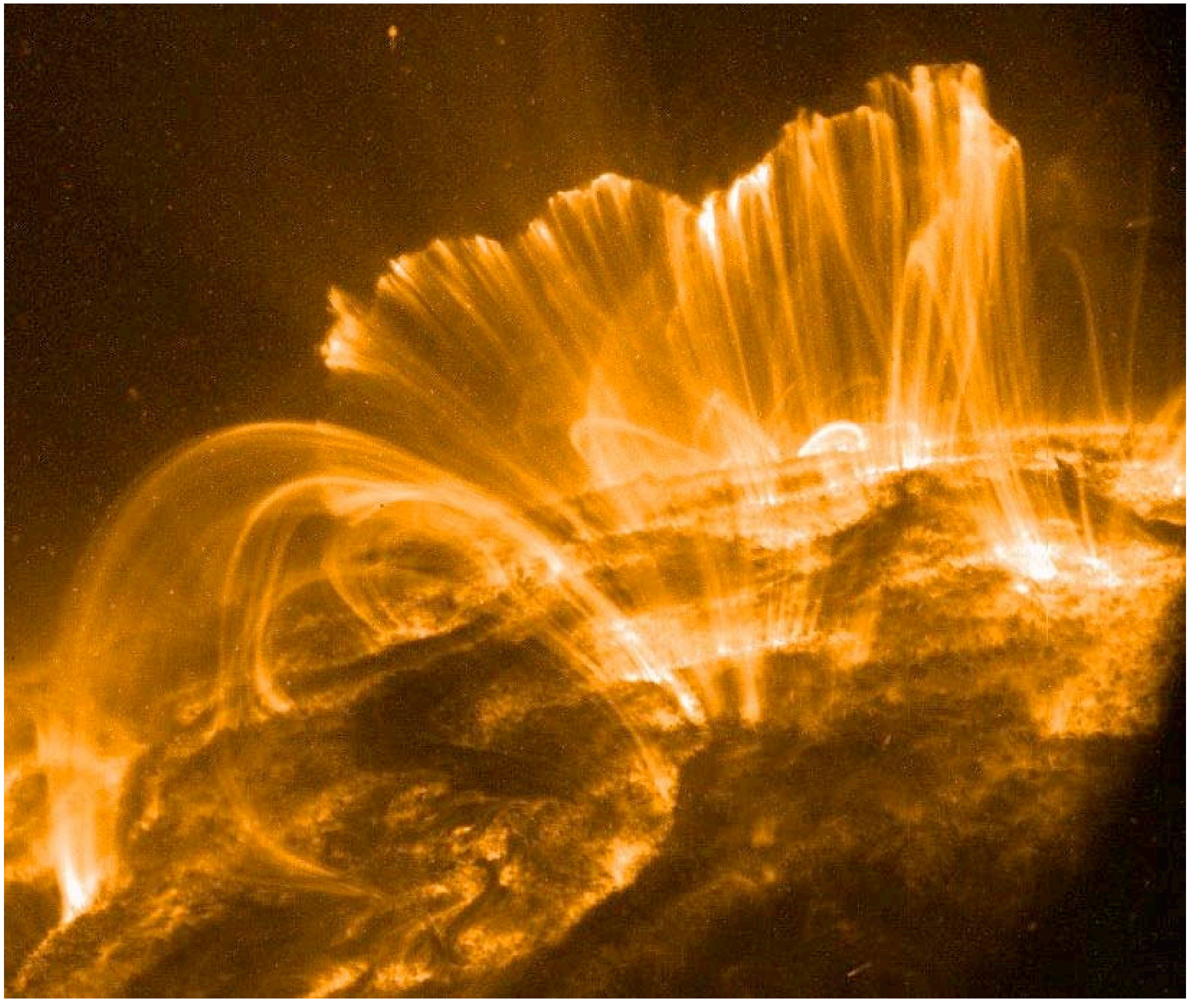


Fig. 23. Characteristics of EMHD currents to a pulsed electrode in a uniform magnetoplasma. The current density lines form right-handed spirals due to the presence of both field-aligned currents and azimuthal electron Hall currents. The J-lines from the electrode penetrate a finite distance into the plasma before spiraling back to the return electrode in the back of the disk electrode. A current tube has been constructed from the measured data. It's enclosed current is conserved and the J-lines lie on its surface. 1997 IPELS meeting on Maui, Hawaii, "Whistler Waves in Space and Laboratory Plasmas" given by Professor Reiner L. Stenzel, J. M. Urrutia.

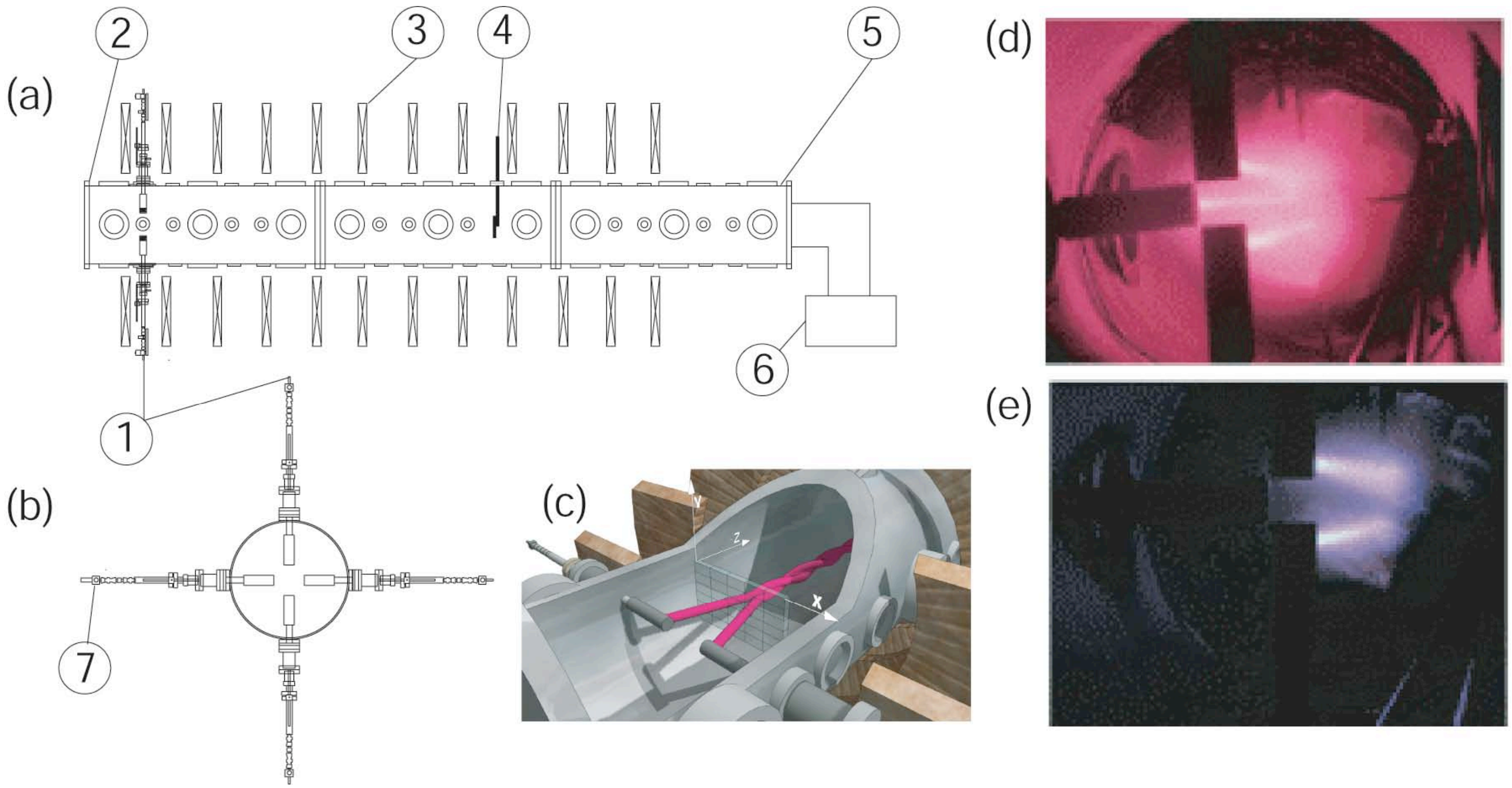
Magneto Hydro Dynamics MHD

- MHD model presumes a single fluid with mass density
  - $\rho = n_i m_i + n_e m_e \approx n(m_i + m_e) \approx n\, m_i$
- Charge density
  - $\sigma = (n_i - n_e)e$
- Mass velocity
  - $\mathbf{U} = (n_i m_i \mathbf{u}_i + n_e m_e \mathbf{u}_e)/\rho \approx \mathbf{u}_i + (m_e/m_i)\,\mathbf{u}_e$
- Current density
  - $J = e(n_i \mathbf{u}_i - n_e \mathbf{u}_e) \approx ne(\mathbf{u}_i - \mathbf{u}_e)$
- Single fluid equation of motion
  - $\rho\, du/dt = \{\partial u/\partial t + u \bullet \nabla u\} = \sigma E + jxB - \nabla p$
- Resistive MHD includes finite resistivity
  - $E + uxB = \eta J + (1/ne)\{jxB - \nabla p\}$

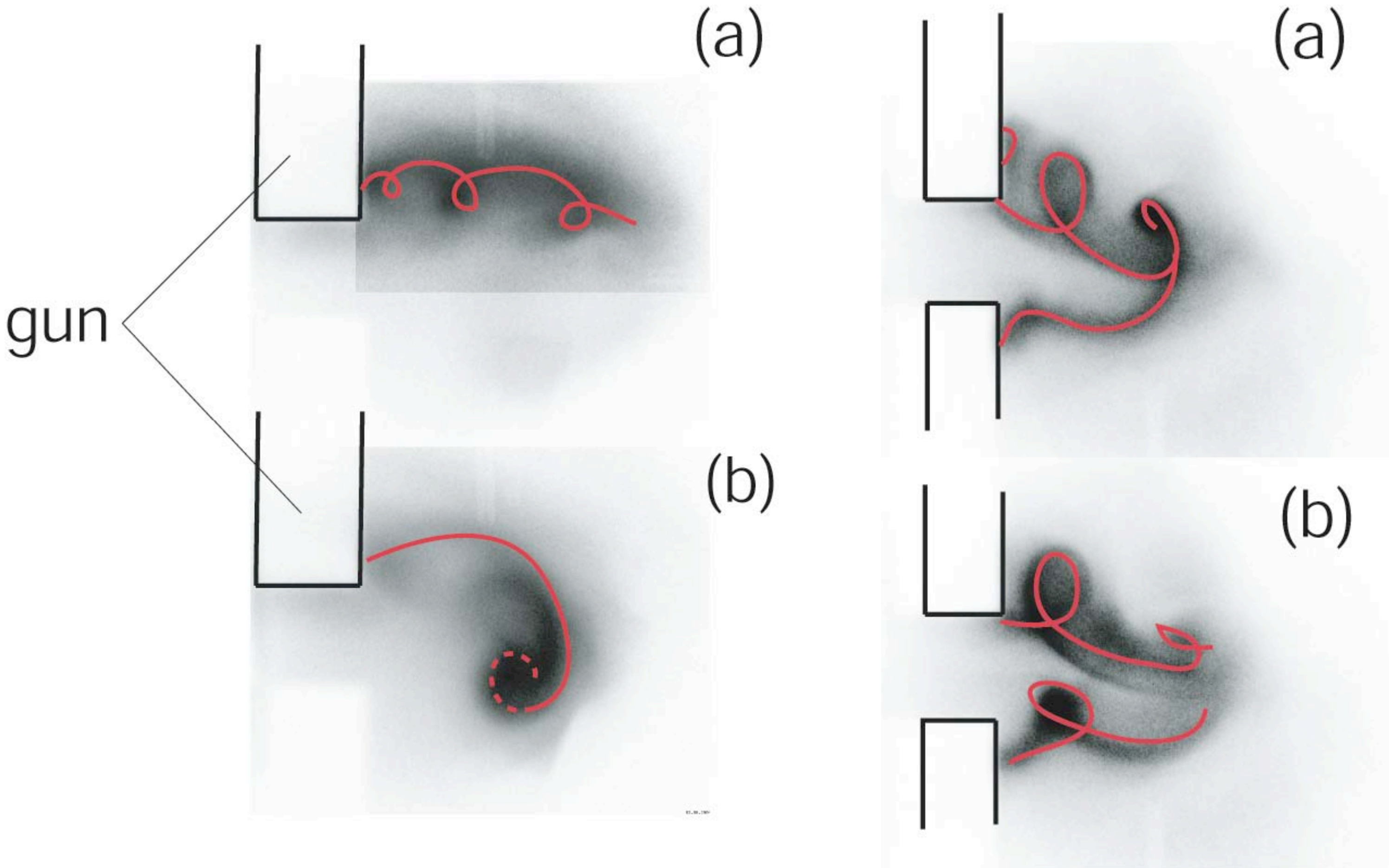
Solar arcades: fluid and magnetic structure



Relaxation Scaling Experiment (RSX) in P-24



RSX flux ropes relax and twist up



Alfven waves & MHD

- A notable property of MHD plasmas was discovered by Hannes Alfven in 1942
  - Michael Faraday had shown in 1800’s that stresses in the magnetic field are equivalent to a pressure transverse to the B field and a tension along the field lines.
  - Alfven showed that certain waves can propagate along the field
  - Analogous to waves on a taut string “Alfven waves”
  - Sound and Alfven speeds

Stability
Unstable plasma systems without collisions

- Stability is one of the most important and recurring problems in plasma physics
- Ideal plasma has zero collisions
  - Certain situations may be theoretically conceivable
  - But they wont survive if they are unstable
  - Fusion devices, eg tokamaks, RFP,
  - Buoyancy instability for flux tubes trapped in suns photosphere
  - Two stream instabilities

Stability
Unstable plasma systems due to collisions

- Finite *resistivity* (collisions) enables the resistive decay of currents in the system
- This is normally very slow in astrophysical settings
- However Dungey realized (1953) that resistive diffusion can lead to strong concentrations of current that then speed up the diffusion process
  - Resistive instabilities
  - Tearing modes, reconnection, solar flares

Complex systems

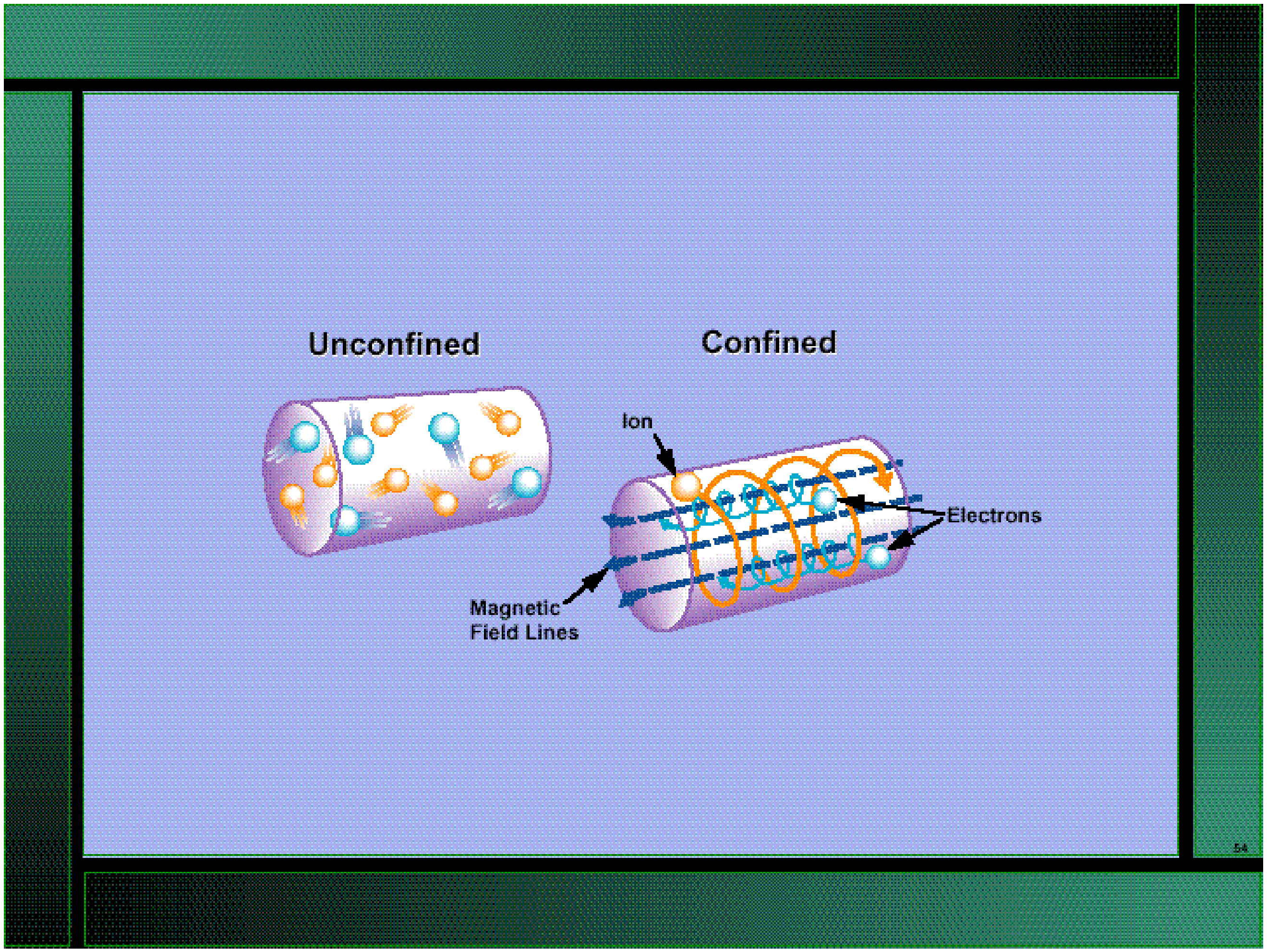
- Plasma systems can exhibit self organized behvior of high complexity
- Self organization occurs in many arenas
  - Space & astrophysics, biosystems, self assembly of micro and nano components, protein folding
  - *Selective decay* processes, thermodynamics
    - Dissipation of some invariant on small scales (eg energy in eddies, turbulence)
    - Persistence of other quantities on larger spatial scales (e.g. helicity)
- *Chaos* … a cottage industry

Confinement is not always perfect (or even good)

- Collisions between particles enable diffusion across magnetic field
  - Pitch angle scattering
- Kills trapping in
  - fusion devices
  - Planetary magnetospheres
  - Coronal flux tubes
- Collisions tend to dissipate highly ordered motions in wave propagation

Confinement means that particles leisurely linger => interact collectively

magnetic confinement here is one example



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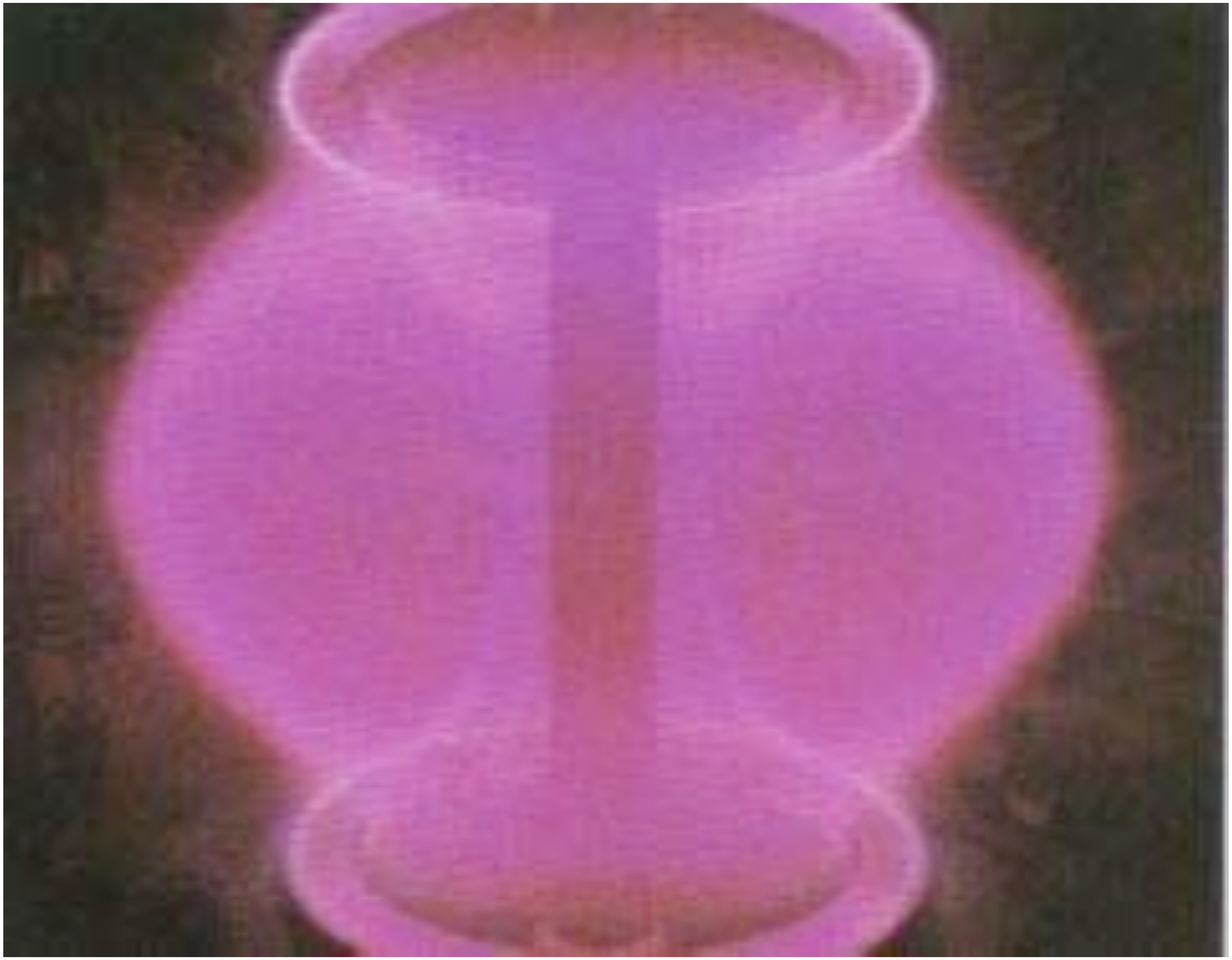
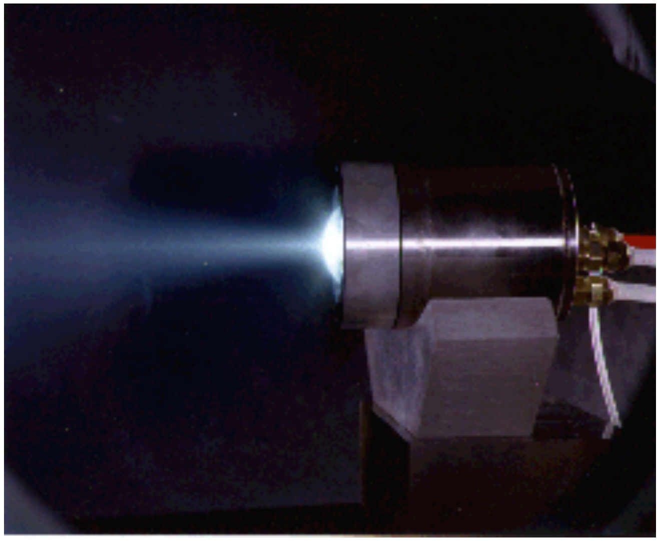
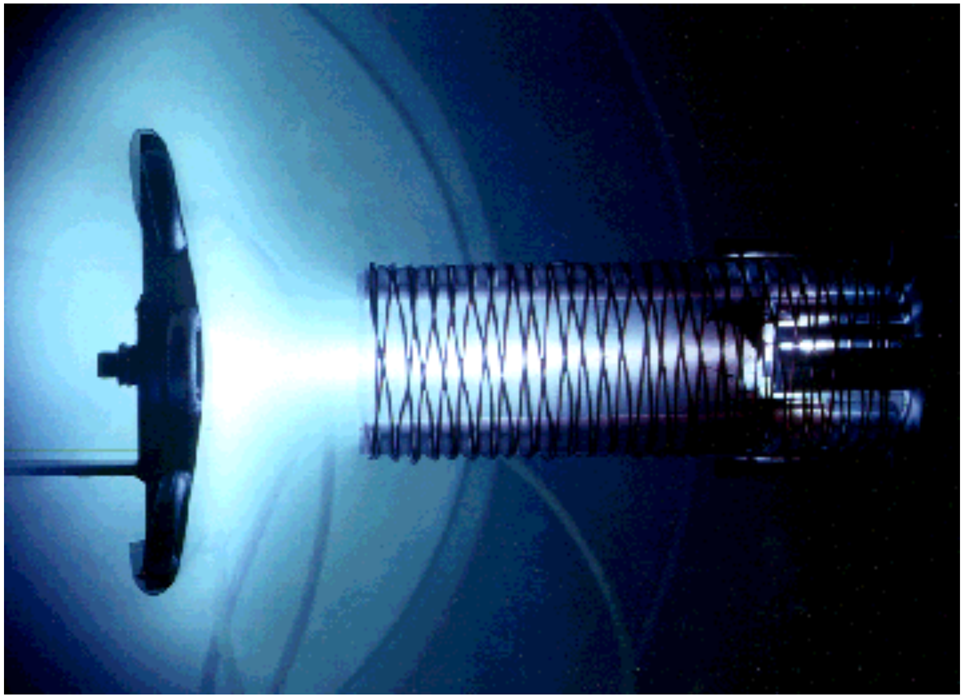


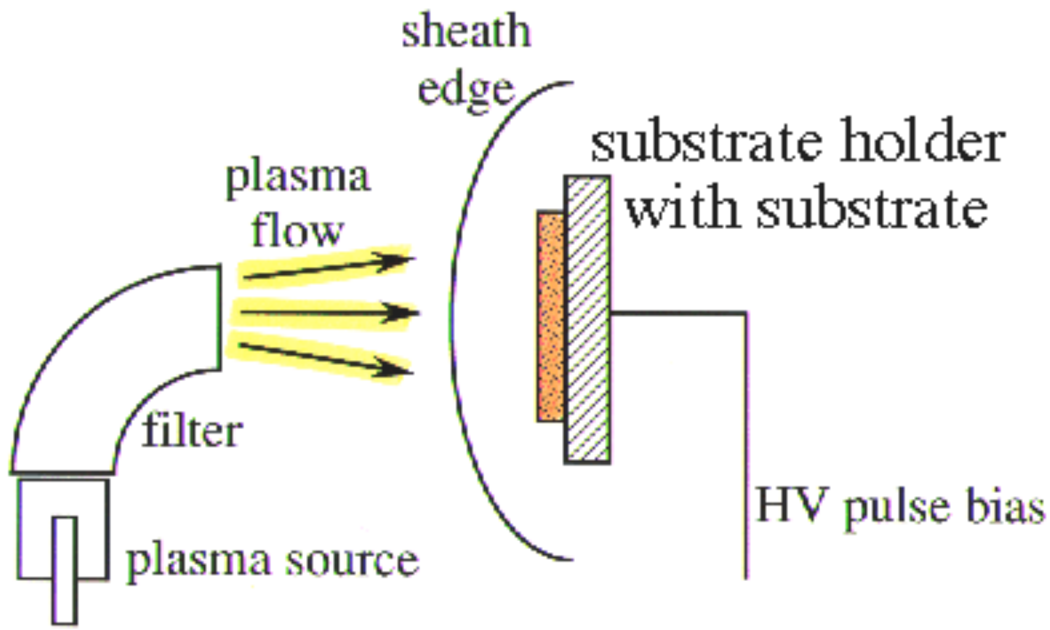
Industrial applications of plasma processing of materials

- Plasma chemistry
- Surface modification
- Semi conductors
  - Etching
  - Oxiding
- Plasma spray, torch
- Decontamination
- Gas lasers
- Solid state plasmas
- Fusion
- Space physics

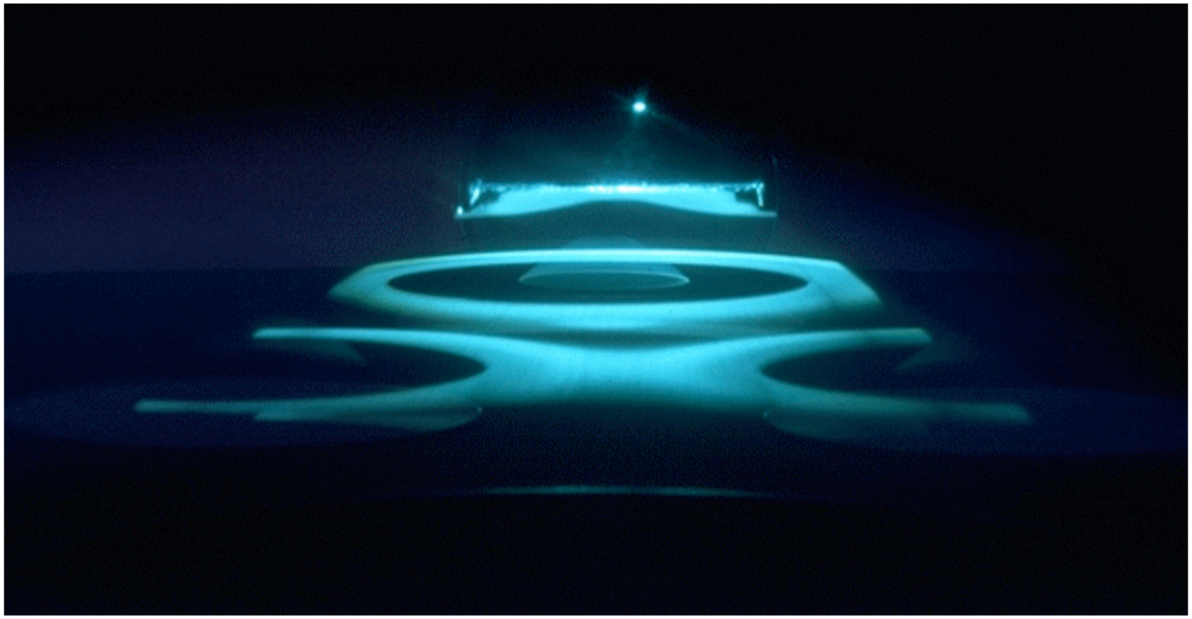


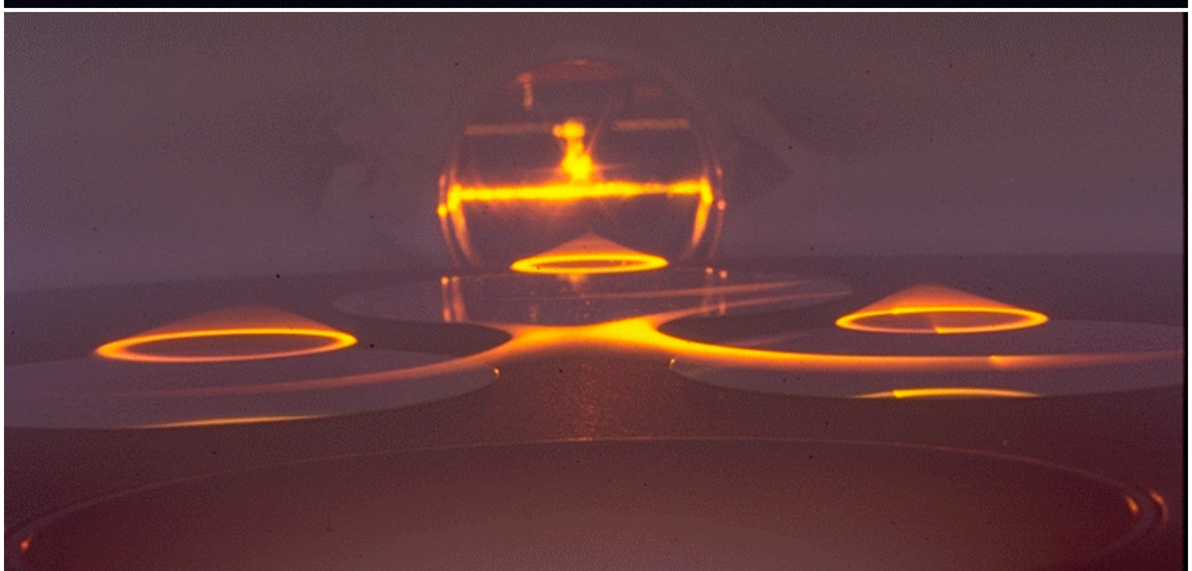


PSII surface modification



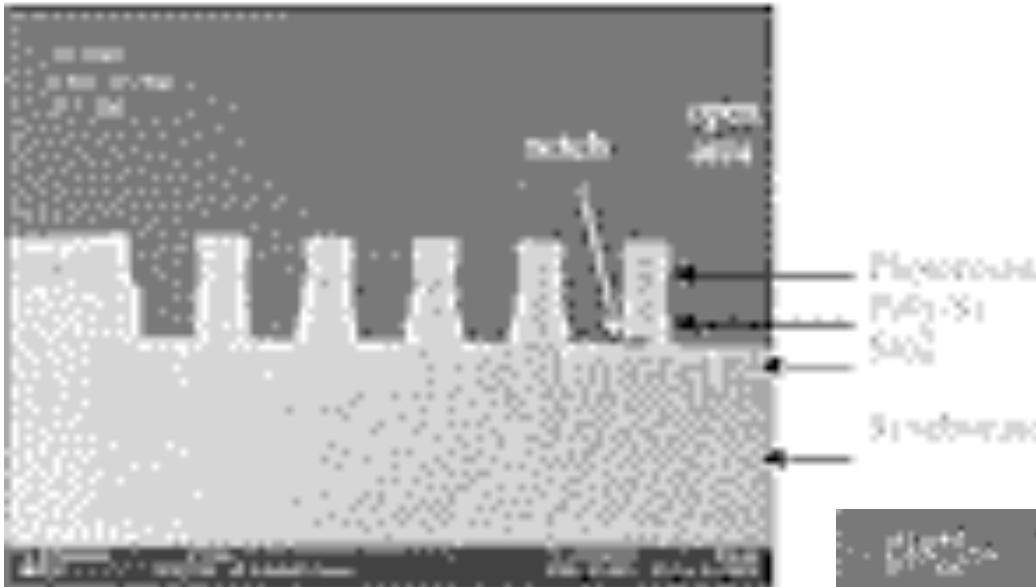
Suspended dust in a plasma processing reactor (Selwyn)

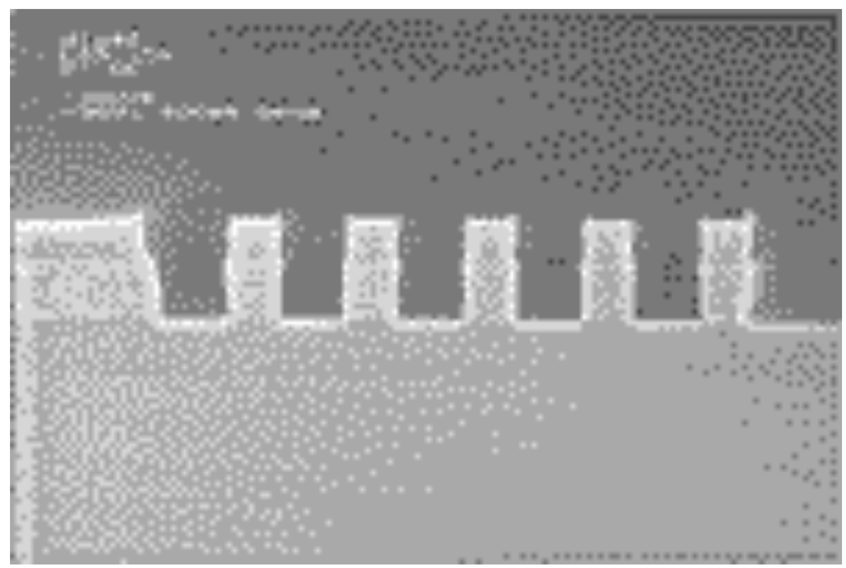




Plasma arc light bulb (Sylvania)

Plasma etching of silicon (T Quick, Univ Wisc ERC)





Handy formulary

- Debye length
  - $\lambda_D(cm) = 740\ [T_e(eV)/n(cm^{-3})]^{1/2}$
- plasma frequency
  - $f_{pe}(Hz) = 9000\ n_e^{1/2}(cm^{-3})$ electrons
  - $f_{pi}(Hz) = 210\ n_e^{1/2}(cm^{-3})$ ions
- gyro radius
  - $r_{gi}(cm) = 100\ T^{1/2}(eV)/B(Gauss)$ ions
  - $r_{ge}(cm) = 2.4\ T^{1/2}(eV)/B(Gauss)$ electrons
- Thermal speed
  - $v_{e,th}(cm/sec) = 4.2x10^7\ T_e^{1/2}(eV)$
  - $v_{i,th}(cm/sec) = 10^6\ T_i^{1/2}(eV)$

Summary

- Plasmas are pervasive - 99% of our universe
- Many examples in everyday life, applications, technology, nature
- Fluids with electrical and magnetic forces
- Experimentally and computationally accessible
- Basic physics is still unfolding - an adventure

Wave fields in 3D

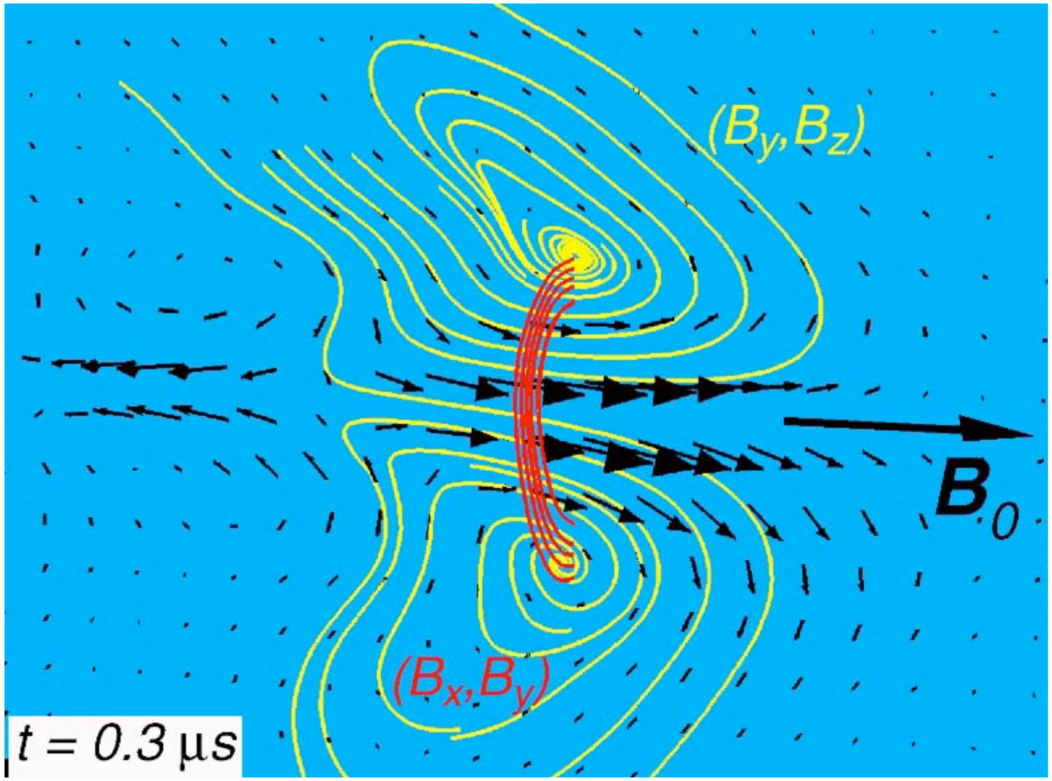


Fig. 14. Measured vector magnetic field of a whistler wave packet showing a 3D vortex topology as emphasized by the linked solenoidal and toroidal field lines [from Urrutia et al, "Pulsed Currents carried by whistlers. III: Magnetic fields and currents excited by an electrode", Phys. Plasmas 2, 1100, 1995].